Short Block-length Codes for Ultra-Reliable Low Latency Communications

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10th April, 2025

Introduction & Motivation

- URLLC: Critical feature of 5G and beyond
- Requirements:
  - Ultra-high reliability (up to $1 - 10^{-9}$)
  - Ultra-low latency (down to 0.1ms)
- Challenging conflict between reliability and latency
- Short packets reduce latency but sacrifice coding gain
- Strong codes increase reliability but add processing delay
- Key challenge: Optimize the reliability-latency tradeoff
- Applications beyond 5G promise (e.g., tele-surgery) demand even stricter requirements

URLLC Requirements

Application Requirements:

- **Factory Automation, Tele-surgery:**
  - Strictest reliability requirement ($1 - 10^{-9}$)
  - End-to-end latency below 1ms
- **Smart Grids, Tactile Internet, ITS:**
  - More relaxed reliability ($1 - 10^{-3}$ to $1 - 10^{-6}$)
  - Latency between 1-100ms
- **5G URLLC Target:**
  - Reliability of $1 - 10^{-5}$
  - User plane latency of 1ms
- **Beyond 5G Needs:**
  - Power electronics industrial control: 0.1ms latency with $1 - 10^{-9}$ reliability
  - Requires special standards and approaches

Channel Coding: Key Metrics & Benchmarks

Key Metrics:

- **Latency Components:**
  - Transmission time (target: hundreds of microseconds)
  - Propagation delay (distance-dependent)
  - Processing delay (encoding/decoding, channel estimation)
  - Retransmission time (must be minimized)
- **Reliability:** Success probability within latency constraints
- **Flexibility:** Bit-level granularity of code rate and size

Performance Benchmark:

- Normal Approximation (NA):

$$R = C - \sqrt{\frac{V}{N}} Q^{-1}(\epsilon) + \frac{1}{2N} \log_2(N)$$

- Incorporates finite block length effects
- Tighter than Shannon's limit for short blocks
- Gap increases as block length decreases

Candidate Short Block-length Codes

- **BCH Codes**
  - Powerful cyclic codes
  - Guaranteed error correction capability
  - Optimal order statistics decoding (OSD)
  - Large minimum distance
  - Limited flexibility
- **Convolutional Codes**
  - Tail-biting CC (TB-CC)
  - High performance with large memory
  - Complex decoding for large memory
- **Turbo Codes**
  - Good for medium/large blocks
  - Iterative MAP decoding
  - Good HARQ support
- **LDPC Codes**
  - Near-capacity for large blocks
  - Protograph-based for short blocks
  - Low complexity belief propagation
- **Polar Codes**
  - Channel polarization
  - SCL/CA-SCL decoding
  - Good for short control channels
  - Chosen for 5G eMBB control

Performance Comparison I: Reliability

Setting: Codeword length N=128, Rate R=1/2, BI-AWGN channel, MLD

Key Observations:

- **Extended BCH codes:**
  - Closest approach to Normal Approximation benchmark
  - Only 0.1dB gap at BLER=10^{-7}
- **TB-CC with m=14:**
  - 0.1dB gap to NA at BLER=10^{-5}
  - Gap increases to 0.3dB at BLER=10^{-7}
- **LDPC codes over large Galois field ($\mathbf{F}_{256}$):**
  - Similar performance to TB-CC with m=14
- Performance ordering: eBCH ¿ TB-CC ¿ LDPC (F_{256}) ¿ Polar+CRC ¿ LDPC (binary) ¿ Turbo

Performance Comparison II: Rate vs. SNR

Setting: Codeword length N=128, BLER=10^{-4}, BI-AWGN channel

Key Observations:

- **BCH codes with OSD (order 5):**
  - Perform very close to normal approximation
  - Outperform other codes at all SNRs
  - Complex decoding, especially at lower rates
- **Polar codes with CA-SCL:**
  - List size L=32 significantly outperforms L=4
  - Increased list size comes with higher complexity
- **eMBB LDPC codes:**
  - Low complexity iterative BP decoding
  - Slightly better than CA-Polar with L=4
- Gap to capacity increases at higher rates for all codes

Complexity vs. Performance Tradeoff

Setting: Block length N=128, rate R=1/2, BLER=10^{-4}

Algorithmic Complexity Comparison:

- **TB-CC with m=14:**
  - Excellent performance (0.3dB gap to NA)
  - Prohibitive complexity ($\sim 10^7$ operations/bit)
- **eBCH with OSD-5:**
  - Best performance (0.1dB gap to NA)
  - High complexity ($\sim 10^5$ operations/bit)
- **Polar with SCL (L=32):**
  - Good performance (0.5dB gap to NA)
  - Moderate complexity ($\sim 10^3$ operations/bit)
- **LDPC with BP:**
  - Reasonable performance (0.8dB gap to NA)
  - Low complexity ($\sim 10^3$ operations/bit)

Conclusion: Polar codes offer the best performance-complexity tradeoff

Research Directions & Recommendations

1. Low Complexity ML-like Decoders

- Enhanced OSD with bounded complexity
- Segmented and sufficient conditioned OSD
- Fundamental balance between performance and complexity

2. Self-Adaptive Coding Schemes

- Eliminate channel estimation overhead (5-8ms in LTE)
- Rate adaptation without CQI feedback

3. Space-Frequency Channel Coding

- Spatial diversity instead of multiplexing
- Reduced OFDM symbols per resource block
- Optimizing diversity for ultra-reliability

Conclusions

- BCH codes with OSD: highest reliability
- Polar codes: good balance with SCL
- TB-CC: excellent with large memory